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3-D Wave-Structure Interaction with Coastal Sediments – A Multi-Physics/Multi-Solution-Techniques Approach

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LONG-TERM GOALS

The long term goal of this research is twofold: (1) develop an advanced multi-physics, multi-scale model with a multi-numerical solution techniques approach to predict nonlinear dynamic behavior of surface and sea-bottom impact, and subsequent burial and flow-induced motion of flexible structures and surrounding sediments in the marine environment; and (2) calibrate resulting models with experimental and field measurements. The predictive capabilities developed in this research will be integrated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

OBJECTIVES

The deployment of mine via airdrop and subsequent sea surface impact, sinkage, sea-bottom impact, burial and scour around sediments is of vital interest to the Navy. Until recently, no numerical codes that can accurately model and simulate this sequence of dynamic motions and their effects on the overall burial behavior at the sea bottom are available. The major objectives of this research include assessment of the state-of-the-art analytical and numerical modeling capabilities, evaluation of the predictive capabilities of the numerical codes for coupled dynamic motions of submerged mines on a seabed in the marine environment, and further improvement of these codes to suit naval analysis, design and operational needs. The numerical predictive capability of these codes will be calibrated against experimental results and field observations.

APPROACH

The dynamic behavior of sea-surface impact and submergence of air-dropped mines and their subsequent interaction with surrounding sediments has been of interest to the Navy in recent years. During 1960s-1980s, U.S. Naval scientists developed three burial prediction models that can be used for mine countermeasure tactical planning and for development of environmental support: sea-surface impact, sea-bottom impact burial, sand ridge migration, and wave-induced scour. Capabilities for accurate modeling and prediction of motions of mines impacting the sea surface and bottom, and their

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effects on the subsequent burial behavior considering the detailed physics of the entire coupled mine-fluid-sediment-seabed “system” are needed. In this project, we focus our research efforts on two 3-dimensional (3-D) multi-physics, multi-solution-techniques numerical codes: (1) LS-DYNA – a commercial code, and (2) a series of in-house research codes with Navier-Stokes fluid and a number of sediment transport models.

The overall objectives of this research project will be achieved through the following tasks: first we will (1) conduct a thorough review of literature on mine-fluid-sediment interaction to determine the state-of-the-art analytical and numerical modeling capabilities; (2) evaluate the current predictive capability of LS-DYNA for coupled dynamic motions of submerged mines on a seabed in the marine environment; (3) identify development needs and further develop LS-DYNA for coupled fluid-structure-seabed interaction applications. Simultaneously, our group has been developing a series of in-house codes using alternative efficient approaches. We will (4) develop and apply the series of in-house codes to calibrate the computational efficiency of LS-DYNA. We will also (5) examine existing laboratory and field experiments available from ONR on motions of mines on seabed for numerical model calibration; (6) compare numerical predictions of resulting numerical modules developed with laboratory experiment and field data to validate and calibrate the numerical models for further evaluation; (7) conduct parametric studies of characteristic burial and exposure times, and examine other parameters as appropriate; and (8) analyze and document research results.

WORK COMPLETED

First, we developed a new three-dimensional (3-D) coupled fluid-sediment interaction model with bed-load/suspended-load transport for scour analysis around a fixed structure. Starting with (a) a reference bed-load and suspended-load sediment transport model developed by Takahashi et al. (2000), we first introduced (b) an extension to incorporate Nielsen’s modified Shields parameter to account for the effects of in-filtration/ex-filtration flow velocity across the fluid-sand interface on the sediment transport (the modified Shields-parameter model). We then (c) developed a new model to include the influence of the effective stress to account for the stress fluctuations inside the surface layer of the sand bed (the effective-stress model). The three analytical models are incorporated into a 3-D numerical solver developed by Nakamura et al. (2008) to analyze the dynamics of fluid-sediment interaction and scour. The Nakamura-2008 solver is composed of two modules, namely a finite-difference method (FDM) numerical wave tank (NWT) and a finite-element method (FEM) coupled sand-skeleton pore-water module (SWM) (see Figure 1). The predictive capabilities of the three alternative coupled models are calibrated against hydraulic experiments on sediment transport and resulting scour around a fixed rigid structure due to the run-up of a single large wave in terms of the sediment transport process and the final scour profile after the wave run-up.

Second, while implementing the numerical code discussed above, we further developed a nonlinear 3-D two-way coupled fluid-sediment interaction model composed of a generalized Navier-Stokes solver (GNS) with the volume of fluid (VOF) module for water-air interface tracking and a sediment transport module (STM) for fluid-sediment interface tracking. GNS is based on the finite difference method with a turbulent stress model of the large-eddy simulation (LES) to compute incompressible viscous multi-phase flows. STM is used to compute nonlinear bed profile change due to bed-load sediment transport. A two-way coupling scheme was implemented to connect GNS with STM at each time step. To validate the resulting code, the fluid-sediment interaction model was applied to predict the cross-shore profile change of a sloping beach due to breaking solitary waves, and the resulting predictions were compared with measured data from a set of hydraulic tests. Figure 2 shows the computational domain of FSM, i.e., the main solver, GNS, and the two surface-tracking modules, VOF and STM. As sketched in the figure, GNS is applied to all fluids including air, water, and pore water in porous media. VOF is used to track the water-air interface motion, while STM is implemented to track the fluid-sediment interface motion.

As part of the initial phase of this project, we also focused on the evaluation of multi-physics code LS-DYNA for prediction of impact, burial and flow-induced motion of mines and its ambient sediments. During the past couple of years, we conducted an exhaustive study to understand and implement the Smoothed Particle Hydrodynamics (SPH) method in LS-DYNA for the mine burial process. We have also conducted comparisons of advanced FE methods, ALE (Arbitrary Lagrangian and Eulerian) and SPH formulations to evaluate their capability and efficiency in modeling mine scour. A numerical wave generation experiment was carried out using LS-DYNA. To comprehend the capability of LS-DYNA in handling fully saturated sandy seabed (cohesionless soil) the wave generation experiment was carried out over a movable sandbed and the waves were modeled by direct numerical simulation governed by the incompressible Navier-Stokes equation. For the seabed, three existing representative soil models in LS-DYNA were investigated. They were all based on the Drucker-Prager soil model derived from either the Mohr-Coulomb failure surface or the Modified-Mohr–Coulomb failure surface. The simulations utilized a continuum approach (ALE) to model each of the fluid, sand, solid mediums.

The SPH method with various formulations can simulate different dynamic fluid flow problems, such as inviscid or viscous flows, compressible or incompressible flows. Initially, the SPH technique available in LS-DYNA was applied to incompressible dynamic fluid flow patterns**.** A series of numerical tests were carried out to examine the capability and efficiency of SPH formulations in simulating benchmark fluid dynamic problems. These tests include simulation of the Poiseuille flow and Couette flow. The results of these simulations showed that this approach can be furthered to understand the scour around a bottom mine. As an important step to achieve the goal of modeling the complex FSI phenomena like mine scour, it is imperative to examine the way SPH and FE couple in LS-DYNA. For this purpose, benchmark problems like dam break in a tank and wave overtopping a rigid deck are considered. The following were few of the simulation tests that were successfully run as a precursor for the applications of SPH to various coupled FSI problems.

The applications of SPH to coupled FSI problems can be categorized in two different categories:

1) FE-SPH coupling simulations: (i) high velocity impact (HVI) of a water drop on a plate; and (ii) solid impacting a fluid domain.

2) Pure SPH domain with SPH-SPH coupling simulations: (i) gravity test for a pure SPH fluid domain; (ii) Dam break- case I: rapid opening of the gate; (iii) dam break- case II: water impacting a rigid cylinder; (iv) dam break- case III: water impacting a flexible cylinder; (v) Mine Burial simulation using a pure SPH domain; and (vi) wave overtopping.

We found from the previous simulations that SPH can couple very well with FE through the contact algorithms. There is not much distortion of the elements at the contact points between FE and SPH. We are actively working on the aspect of treating the fluid domain in ALE (where the wave action is large) and FE for the bottom domain where it contacts the sand (which is pure SPH). With this setup we can have a finer SPH mesh (slave) than the FE mesh (master) and any nodes to surface contact should work.

RESULTS

For the 3-D coupled fluid-sediment interaction model with bed-load/suspended load transport, it is found that, among the three models considered, the proposed effective-stress model most accurately predicts the scouring process around the seaward corner of the structure. The results also reveal that the deposition and erosion patterns predicted using the effective-stress model are in good agreement with measured results, while a scour hole at the seaward corner of the structure cannot be always predicted by the other two models [1].

For the nonlinear 3-D two-way coupled fluid-sediment interaction model, it is found that the fluid-sediment model of a physical experiment (Figure 3) predicts reasonably well the sediment transport and the resulting beach profile change (Figure 4) and the wave surface profile (Figure 5) [2]. The sensitivity of the sediment transport on model parameters is also analyzed. Finally, the fluid-sediment interaction model is applied to predict the three-dimensional local scour in front of a quay wall due to a jet flow to demonstrate its applicability to general problems (Figure 6) [3].

For the LS-DYNA model, it was found that a pure continuum approach is not able to capture the complex motion of the sand particles during the settling and burial of the mines. On the other hand, a discrete approach such as smooth particle hydrodynamics (SPH), which relies on the equations of state to represent the material behavior, may be a viable alternative. Retaining a similar wave generation experiment over a sand bed, a comparative study to understand scour scenario around a solid object (mine burial) was conducted using the SPH method available in LS-DYNA (Figure 7). We found the code to be able to successfully simulate a number applications of SPH for various coupled FSI problems including: (1) high velocity impact (HVI) of a water drop on a plate (FE and SPH coupling) (2); solid impacting a fluid domain (impact problem using FE-SPH coupling); (3) gravity test for a pure SPH fluid domain; (4) dam break- case I: rapid opening of the gate; (5) dam break- case II: water impacting a rigid cylinder; (6) dam break- case III: water impacting a flexible cylinder; (7) mine burial simulation using a pure SPH domain; (8) wave overtopping; and (9) water entry dynamics of a rigid body impacting water. The buildup to the modeling of basic fluid dynamic problems using SPH method was furthered to understand the scour around a bottom mine. Having the successful simulation of some of the benchmark fluid mechanics problems using a pure SPH-SPH coupling to SPH-FE coupling and testing the capability of LS-DYNA in handling the complex mine scour problems, we are in the process of enhancing the code to suit the present purpose.

IMPACT/APPLICATIONS

The advanced, state-of-the-art series of in-house research codes and the commercial FE code LS-DYNA adopted in this project, when fully developed, will enhance the modeling, prediction, operation and control capabilities of the complex mine-fluid-sediment-seabed interaction in general and the numerical simulations of flow-induced mine burial impacts in particular. The 3-D numerical codes being developed will provide additional tools to calibrate and validate the accuracy of the numerical predictions of the modules with laboratory experiment and field data. A schematic diagram of ideal numerical models using domain decomposition with various numerical techniques for different domains of the coupled fluid-structure-soil interaction system is depicted in Figures 9 and 10 below. From the computational sketch it can be seen that the fluid domain followed by the structure and the sand can be modeled using four different computational methods. The fluid domain will be modeled using the fully nonlinear potential flow (FNPF) and discretized using the boundary-element method (BEM). Reynolds Averaged Navier-Stokes (RANS) and the particle finite element method (PFEM) will be used in the water/mine/sand domain. Sand and the geomaterials around the sand will be modeled using the Smoothed Particle Hydrodynamics method (SPH). The resulting numerical predictive capability will be incorporated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

TRANSITIONS

Analysis and simulation capabilities developed in this research can be useful to the various units of the Navy pertinent to mine deployment, detection, burial clearance process studies.

RELATED PROJECTS

The analysis and simulation capabilities developed in this research will be incorporated into a companion project (N00014-07-1-0207) on the development of an overarching computational framework for analysis and prediction of dynamic motions of naval systems in the marine environment in arbitrary water depth.

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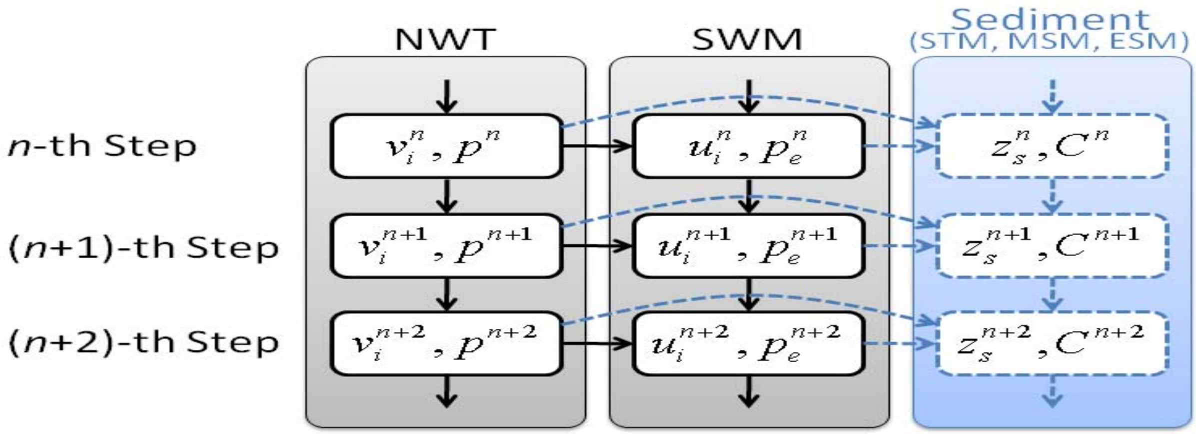


Figure 1. Computational procedure of the coupling technique among the NWT, the SWM, and one of the sediment transport models, i.e., the STM, the MSM, and the ESM.

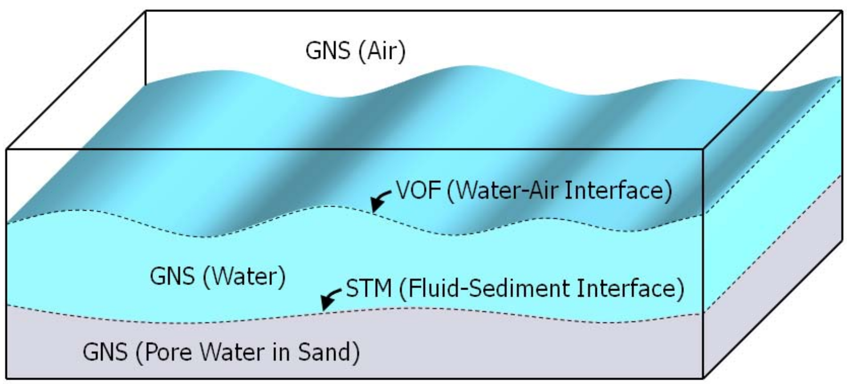
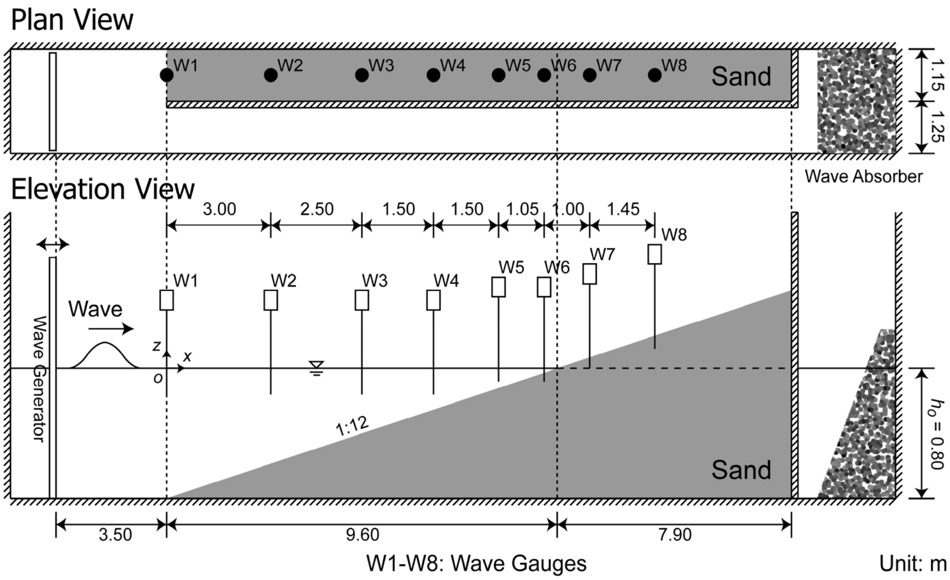
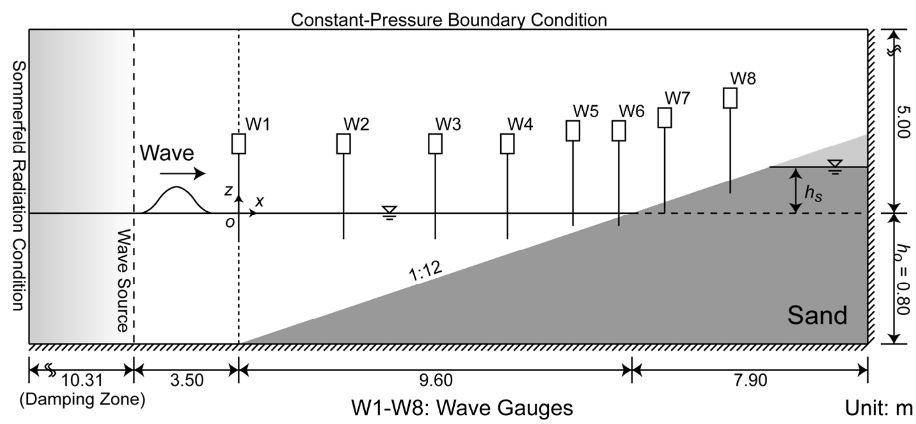


Figure 2. Schematic illustration of the computational domain of FSM (the main solver, GSN, and the two modules, VOF and STM).



(a)



(b)

Figure 3. Wave flume for beach profile change due to solitary waves: (a) experimental setup and the position of wave gauges; and (b) computational domain and the definition of the saturation height.

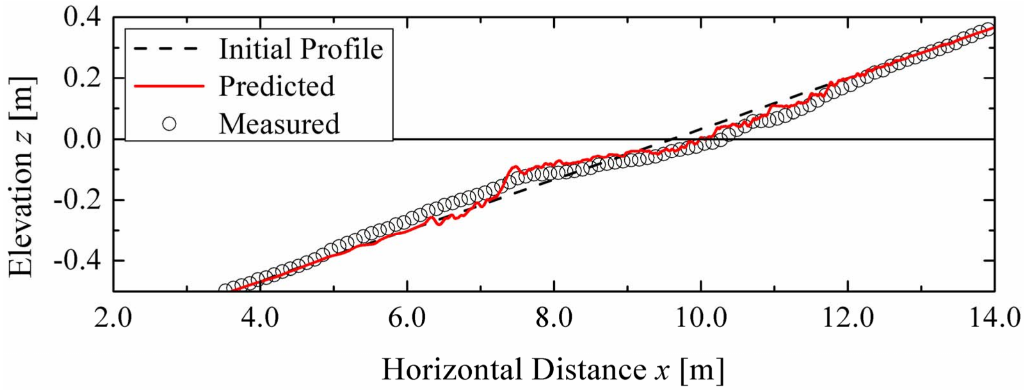


Figure 4. Predicted and measured beach profile change after the fourth wave for the best-fit case.

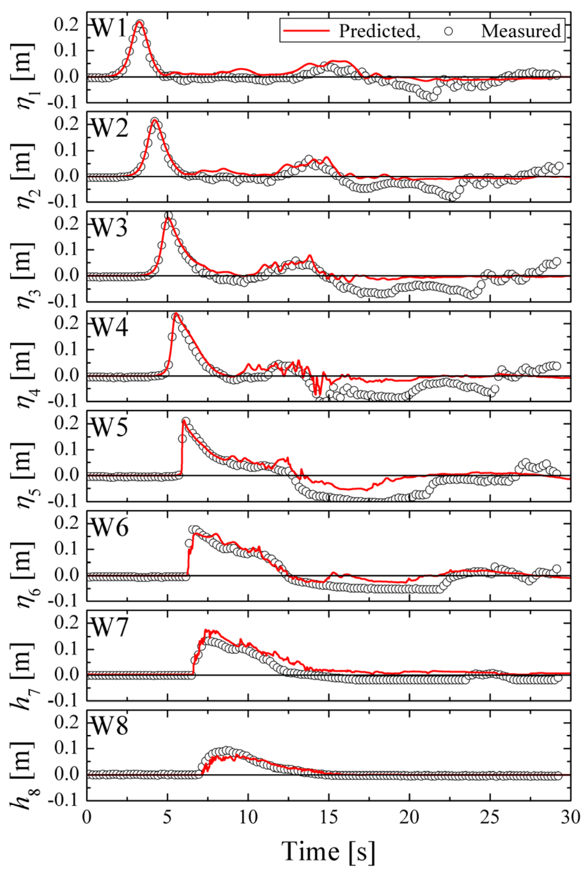
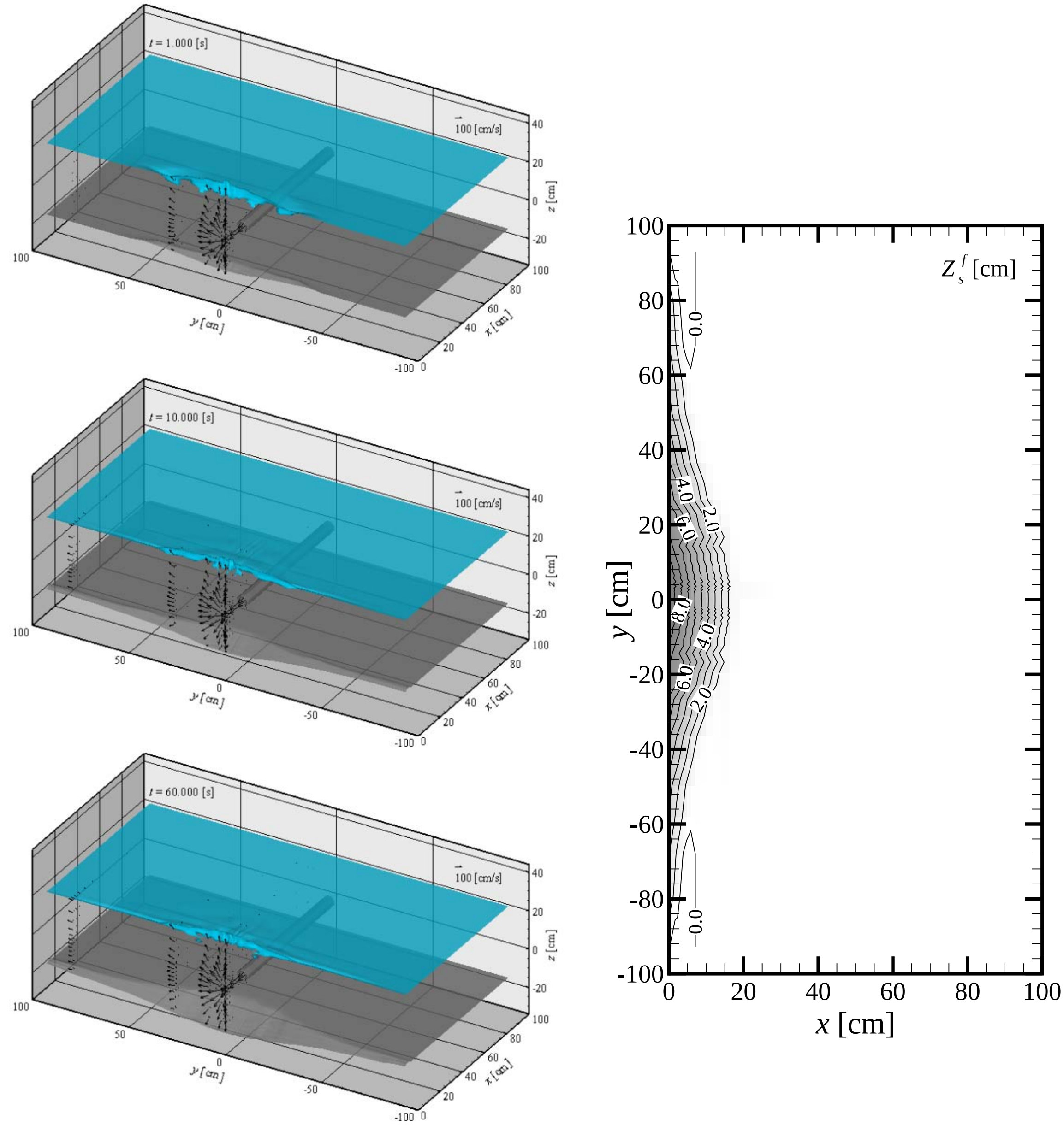


Figure 5. Predicted and measured water surface elevations during the fourth wave for the best-fit



(a) (b)

Figure 6. Computed local scour due to the jet flow: (a) evolution of the scour hole (top: 1.0 s after the flow begins to be generated; center: 10.0 s; and bottom: 60.0 s); and (b) final scour depth at 60.0 s.

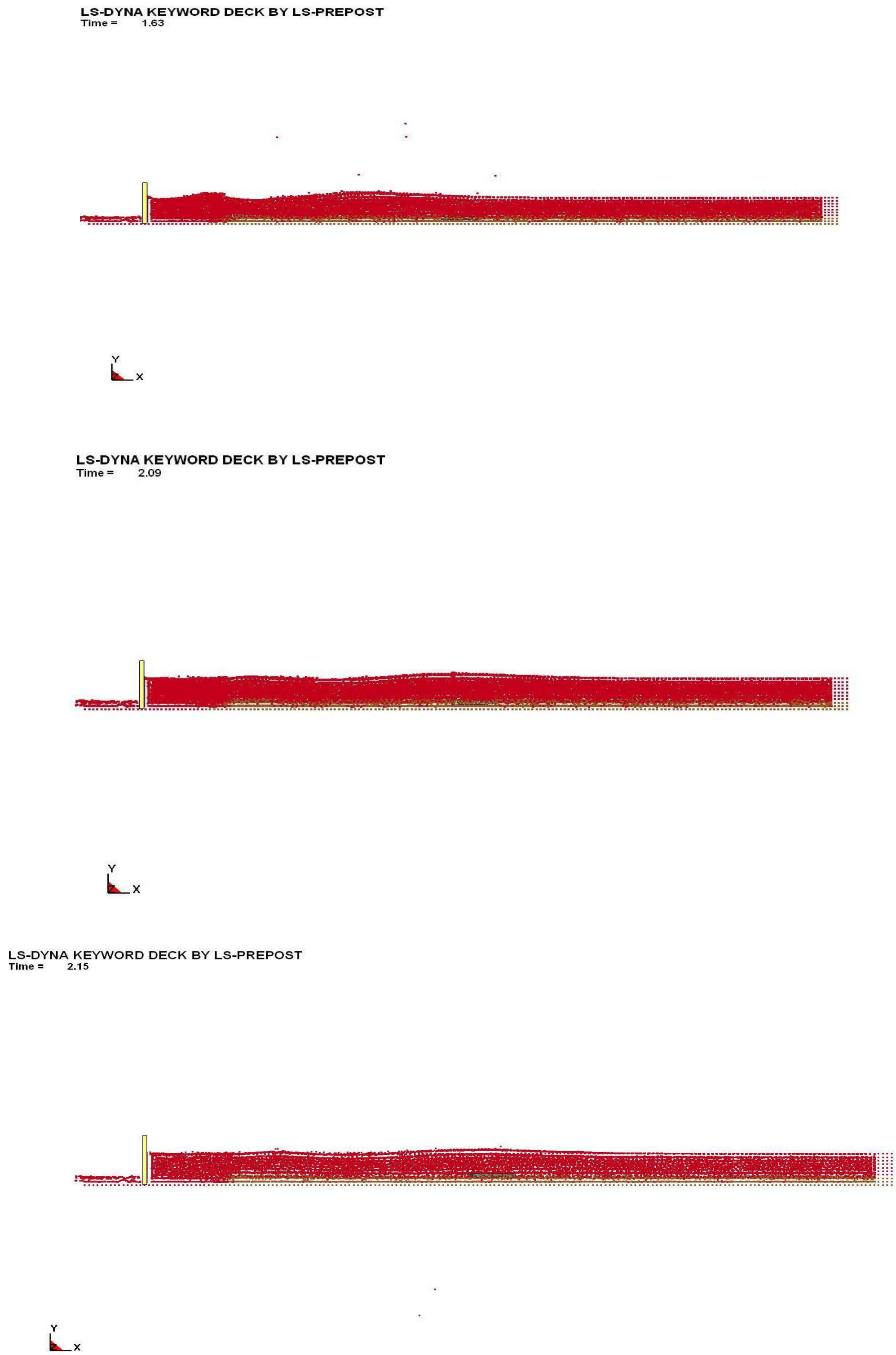


Figure 7. Mine Burial simulation with a wave generation set-up using a pure SPH domain

PUBLICATIONS

T. Nakamura and S.C. Yim, “Development of a Three-Dimensional Coupled Fluid-Sediment Interaction Model and Its Application to Erosion and Scour Phenomena,” *Annual Journal of Civil Engineering in the Ocean*, Japan Society of Civil Engineers, Vol.25, pp.1227-1232 (in Japanese).

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